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A kinematic model for the southern Alaska orocline based on regional fault patterns

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ABSTRACT

Among the most prominent physiographic features of southern Alaska are a series of nested arcuate lineations, including the Denali fault, that parallel the concave-southward southern coastline of the state. These features are generally interpreted as major dextral shear zones that formed in the Late Cretaceous to early Tertiary in response to stresses imposed on the western edge of North America by transcurrent motion and oblique subduction along the North American margin.

South-central Alaska consists of a collage of Paleozoic and Mesozoic tectonostratigraphic terranes and overlap assemblages. Following accretion to the continent, these terranes were transported northward along its margin along strike-slip faults such as the ancestral Denali fault that formed by oblique subduction. The terranes would have arrived at about their present position by Eocene time. It is commonly held that southwestern Alaska rotated into its present configuration by the middle Eocene, in response to impingement of northeast Asia against western Alaska, to form the southern Alaska orocline. Subsequent to this rotation during the middle and late Tertiary, southern Alaska terranes were presumably transported through the Alaska orocline by continued dextral movement along faults on the east limb of the orocline, such as the Denali and Tintina.

Both initial bending of the crust to form the orocline and subsequent transport of crust through the orocline would result in significant crustal shortening within the bend. A model is suggested herein whereby shortening is accommodated by a system of secondary, northeast-trending thrust faults. The distribution of these faults shows a consistent pattern within the bend: the faults appear to splay off at or near the major dextral shear zones and generally occur west of the orocline's axis. That these faults occur where deformation would be greatest to crust driven through the bend suggests that the faults are directly related to crustal dynamics within the bend. If this model is correct, one may infer the sense and timing of motion along many faults that otherwise lack or have limited documented histories.

The interaction of strike-slip and thrust faults suggested by the model is reflected in the rupture sequence of the November 3, 2002, M7.9 Denali earthquake, which involved both initiation of slip along a previously unknown east-northeast–trending thrust fault and subsequent strike-slip motion along the McKinley strand of the east-west–trending Denali fault. This event is likely due, in part, to stresses imposed by accretion of the Yakutat terrane that is presently working its way into the bend of the orocline and deforming as a result of collision. Faulting along the western margin

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of the Yakutat terrane resembles that seen in central Alaska within the hinge of the bend. As such, it likely represents a present-day analog for crustal deformation associated with the orocline and may therefore provide clues to earlier stages of crustal deformation in central Alaska.

Keywords: orocline, southern Alaska, kinematic model, tectonic, faulting.

GEOLOGIC SETTING

South-central Alaska (Figs. 1 and 2), where the effects of oroclinal bending were greatest, consists of an assemblage of Paleozoic and Mesozoic tectonostratigraphic terranes that were well south of their present position (~30°) in the Late Triassic (Hillhouse and Coe, 1994). Two major terranes in south-central Alaska (Fig. 2), the Wrangellia and Peninsular terranes, were apparently amalgamated by the Middle or Late Jurassic (Csejtey et al., 1982) or the Permian (Nokleberg et al., 1994b). Though still south of their present position, they probably docked with North America during the mid-Cretaceous (Nokleberg et al., 1994b). After having accreted to the continent, oblique subduction drove them northward along the continental margin via strike-slip faults such as the ancestral Denali fault (Plafker and Berg, 1994).

In the middle and late Cenozoic, oblique convergence between the Pacific and North American plates resulted in major dextral-slip faulting in interior and southern Alaska and along the western part of the Aleutian-Wrangell arc, involving faults like the Denali, Nixon Fork, and Kaltag. This oblique convergence has been described as a form of tectonic escape of terranes from western Alaska into the Bering Sea, occurring along major dex-

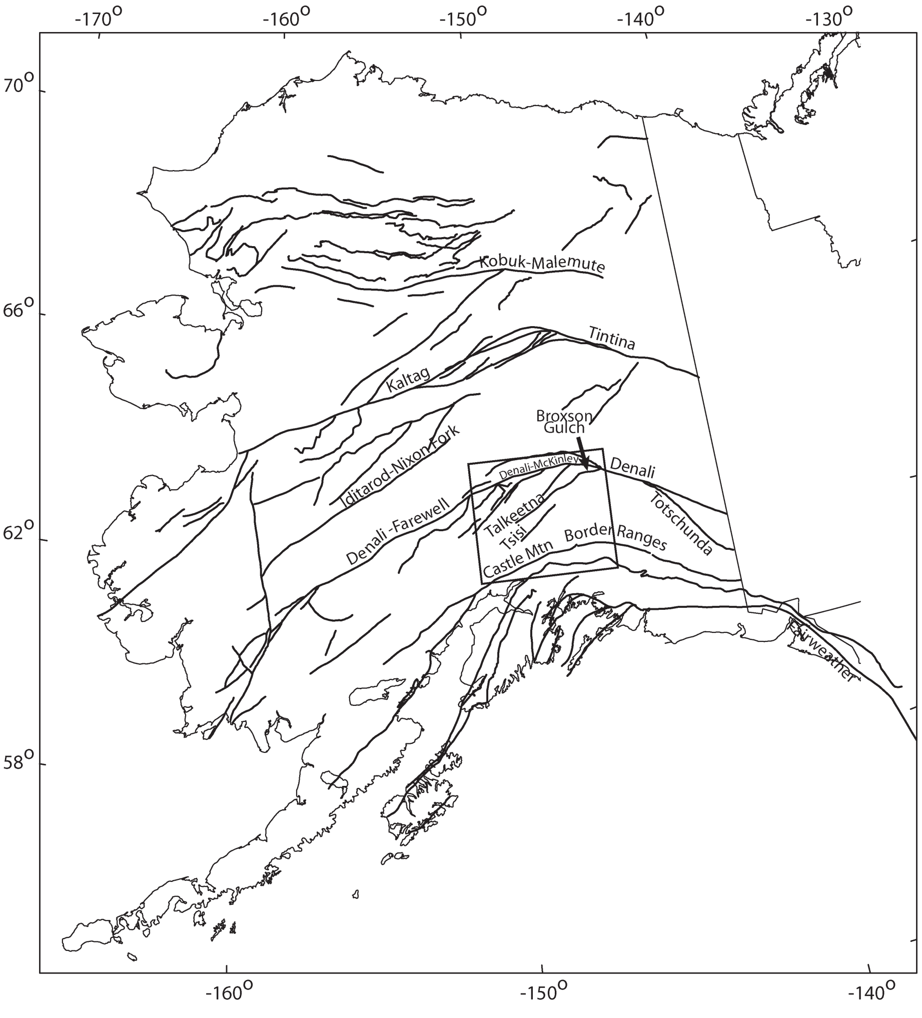


Figure 1. Index map of Alaska showing major Alaska faults compiled from Beikman (1980, 1994), Gemuts et al. (1983), Patton and Moll (1982), Dillon et al. (1985), Grantz et al. (1991), and Nelson et al. (1984).

tral-slip faults (Scholl et al., 1992). Accompanying this was the accretion of a fragment of the Kula oceanic plate (Scholl et al., 1992) and the development of dextral-wrench sedimentary basins during the Late Eocene through Oligocene in association with motion along major dextral-slip faults (Ridgway et al., 2002).

Coincident with crustal extrusion during the Paleocene, it is believed that compression between Eurasia and North America (Plafker and Berg, 1994) resulted in major counterclockwise rotation of southwestern Alaska (Lonsdale, 1988). Southern Alaskan ranges were thus warped, creating a curved mountain chain or orocline. Subsequent to this bending, during middle and late Tertiary time, southern Alaska terranes were forced to move through the bend due to continued dextral movement along faults like the Denali and Tintina.

This paper concerns the deformation in the hinge of the orocline that is expected to have resulted from original bending and from the subsequent transport of crust through the bend due to Cenozoic dextral shear along the major strike-slip system of faults in southern Alaska.

THE OROCLINE AND ALTERNATIVE MODELS

Carey (1955, 1958) defined an orocline as "an orogenic belt with a change in trend, which is interpreted as an impressed strain" (1958, p. 191). He defined the Alaska orocline as the "bend in the trend from the Canadian Rockies and Coast Ranges through the Alaska Range into the Alaska Peninsula" (1958, p. 192), and assumed that these contiguous ranges had once formed a relatively straight line. This bend is also reflected in the concave-southward trend of Late Cretaceous arc-related rocks in southern Alaska and the sharp bend of major transcurrent faults like the Tintina and Denali.

Oroclinal bending, which mainly affected central and southwestern Alaska, is considered to have occurred between the Late Cretaceous and middle Eocene, based on the deformation of Late Cretaceous and Paleogene rocks of the Chugach and Prince William terranes in the axis of the bend and on paleomagnetic data from volcanic rocks of western Alaska (Plafker, 1987; Coe et al., 1985). Paleomagnetic studies indicate that western and south-central Alaska (between the Kaltag fault and Kodiak Island) underwent 44° ± 11° of counterclockwise rotation with respect to stable North America at ~65–50 Ma (Coe et al., 1985; Panuska, 1987; Coe et al., 1989; Panuska et al., 1990; Hillhouse and Coe, 1994). Several mechanisms, including the original form of Carey's orocline hypothesis, have been proposed to account for this rotation (Csejtey, 1992; Coe et al., 1989). These generally fall into two categories: those that consider the bend as an original feature versus those that consider southern Alaska and its

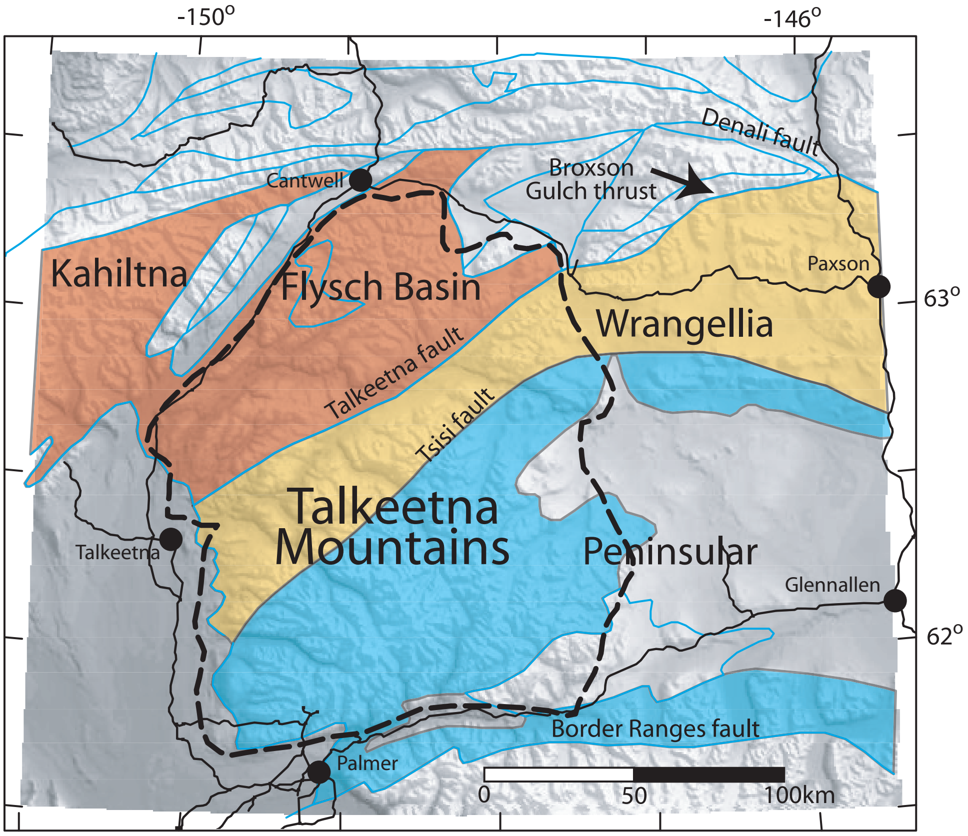


Figure 2. Shaded relief map of the Talkeetna Mountains region (bold-dashed line) showing major tectonostratigraphic terrane boundaries (blue lines). Roads are shown in black. Also identified are the major faults and terranes in the Talkeetna Mountains discussed in the text. Terrane boundaries are after Glen et al. (2002) and modified from Silberling et al. (1994).

ranges as having been originally straight but subsequently bent into their present form (Fig. 3).

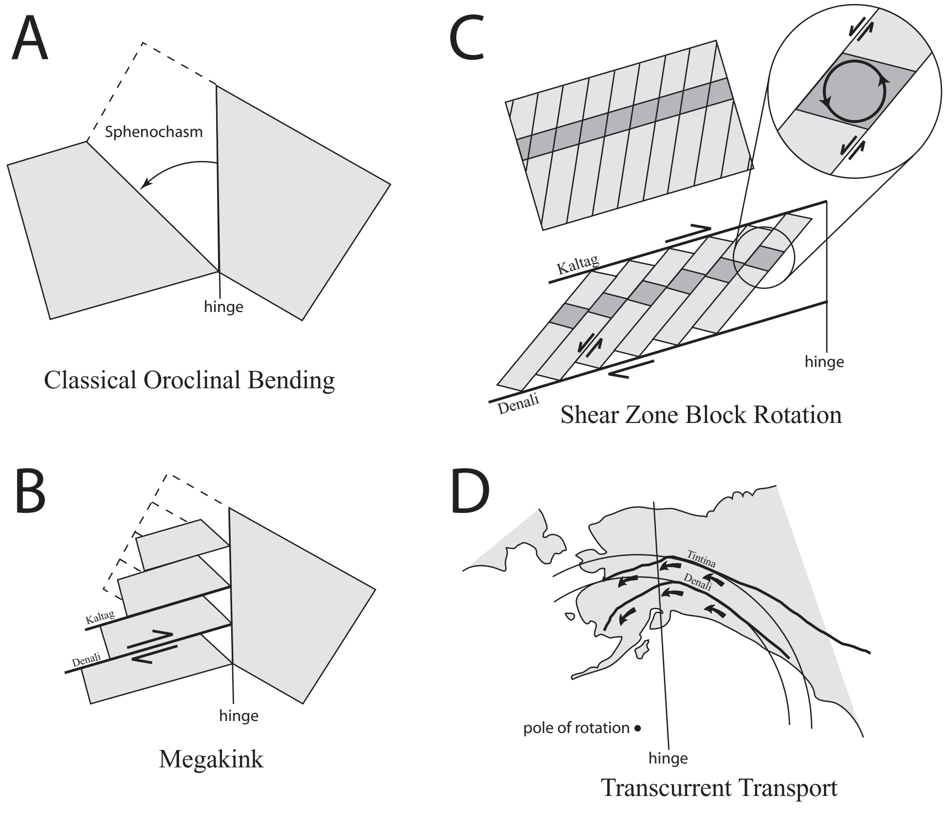
Classical or modified forms of the orocline mechanism (Carey, 1955, 1958), as well as the megakink hypothesis (Grantz, 1966), involve the rotation of western Alaska in response to impingement of Asia on western North America. Carey (1955, 1958) interpreted that the Alaskan ranges were once relatively straight and that subsequent bending produced their present curved configuration and the observed paleomagnetic rotations. The classical model for formation of the orocline (Fig. 3A) entails the wholesale rotation of western Alaska and requires the opening of a large void, for which Carey coined the term "sphenochasm." This model has been summarily rejected on the grounds that there is no evidence for such a feature (Coe et al., 1989). The megakink model (Fig. 3B) overcomes the need for a single, large sphenochasm by invoking several blocks that slide past each other along a series of right-lateral strike-slip faults.

Another category of mechanisms provides an alternative to wholesale rotation of western Alaska by considering the bend as an original feature of southern Alaska. A shear or drag mechanism (Fig. 3C; e.g., Freund, 1974) can produce the appropriate counterclockwise rotation of blocks bounded by concurrent dextral faults, provided there exists a set of secondary sinistral faults. Little support exists, however, for a pervasive set of these secondary faults. A transcurrent transport (or "railroad car") model (Panuska, 1987), on the other hand, accounts for the rotations as the result of translation along curved strike-slip faults (like the Denali and Tintina) through a preexisting bend (Fig. 3D). However, this and related tectonic extrusion models (Scholl et al., 1992) cannot readily explain the rotations observed in far western Alaska, since Tertiary rocks from there, which record counterclockwise rotations, would presumably have been west of the bend at the time of their deposition.

Alternatively, the paleomagnetic rotations may be due to some combination of these mechanisms. For example, even in the case in which the bend in the Alaskan Range resulted from oroclinal folding, transcurrent transport would still likely take place subsequent to bending due to oblique subduction (Miller et al., 2002). In any case, each of the mechanisms proposed to account for the rotations necessitates similar deformation of crust in and around the hinge of the bend (Figs. 4 and 5). This paper offers a model by which this deformation is accommodated.

ALASKA FAULTS AND THE SOUTHERN ALASKA OROCLINE

Perhaps the most prominent features of Alaska are long and arcuate, through-going faults extending from the far southeastern panhandle of the state to the Bering Sea (including the Denali and Tintina faults). They represent important regional geologic structures that have prominent topographic expressions that mimic the concave southward form of the southern Alaska coast and ranges.



Classical Oroclinal Bending

Shear Zone Block Rotation

Megakink

Transcurrent Transport

Figure 3. Models proposed to account for the observed net counterclockwise rotation of western Alaska. These mechanisms fall into two categories: those that consider southern Alaska and its ranges to have been at one time largely straight and subsequently bent into their present form (e.g., A, the classical orocline mechanism of Carey [1955, 1958] and B, the megakink hypothesis of Grantz [1966]), and those that consider the bend as being an original feature of southern Alaska (e.g., C, a shear or drag mechanism [Freund, 1974] and D, a transcurrent transport [or "railroad car"] model [after Panuska, 1987]).

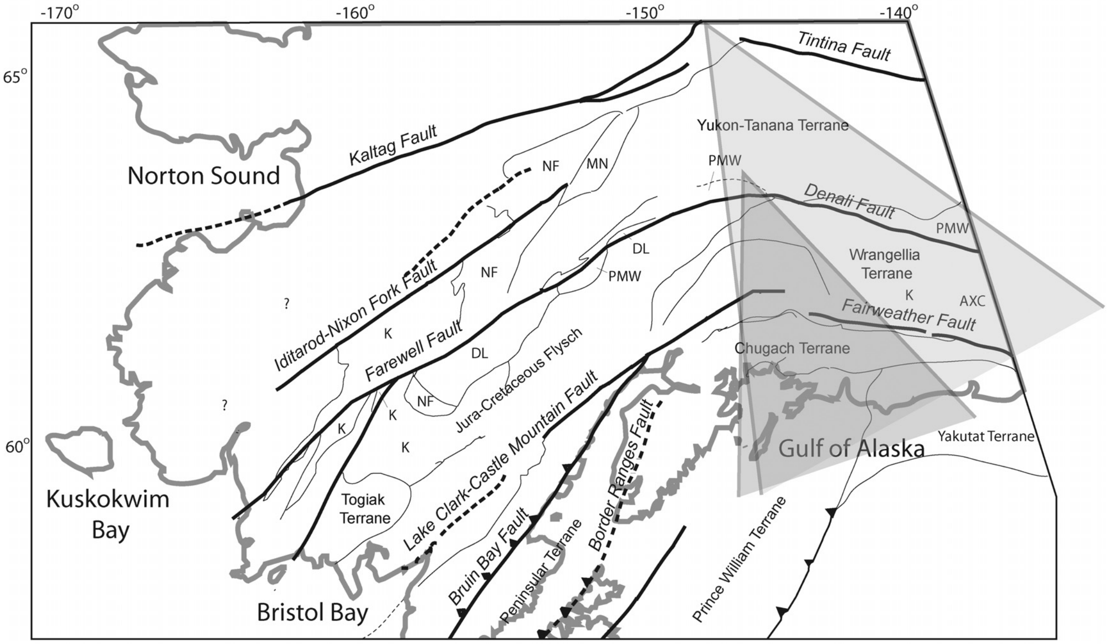


Figure 4. Figure (after Csejtey, 1992) illustrating the wedge of material within the hinge of the orocline that would need to be accommodated by oroclinal bending. Two different shaded wedges are shown for two different placements of the pole of rotation (poles are located at the apex of each wedge). Major faults are shown in black and terrane boundaries in gray.

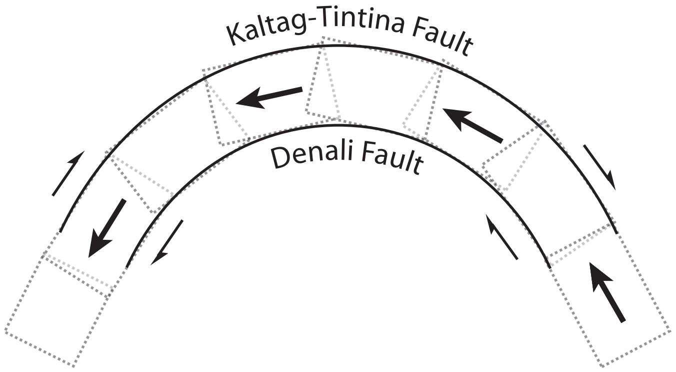


Figure 5. Cartoon illustrating a boxcar model in which blocks of crust are forced through an existing bend. As crustal blocks approach the hinge of the bend, blocks begin to overlap.

Many of these faults have long been interpreted as dextral shear zones (Grantz, 1966). They are conspicuous in a map compilation of fault traces (Fig. 1, compiled from Beikman, 1980; Gemuts et al., 1983; Patton and Moll, 1982; Dillon et al., 1985; Grantz, et al., 1991; Nelson et al., 1984; Nokleberg et al., 1994a) and reflect a primary fault pattern of Alaska (blue lines, Fig. 6).

As a result of dextral shear along these faults, crust is transported around the bend. This, and the original bending to form the orocline, necessitates significant crustal shortening within the hinge. Up until recently, however, crustal structures capable of accommodating this shortening have not been specifically identified. Csejtey (1992), for example, reported that geologic mapping within the Talkeetna Mountains (directly within the hinge of the bend) does not reveal the structural features needed to account for the deformation and suggested that faults, such as the Tsisi (herein named) and Talkeetna (Fig. 2), relate to accretion of terranes in mid- and/or Late Cretaceous time.

A comparison of the neotectonic faults of Alaska (Fig. 7; after Plafker et al., 1994a) and mapped fault traces (Fig. 6) shows that for many of the faults, little or no information on Paleogene faulting is known. Late Cretaceous to early Tertiary displacements on the major transcurrent faults (Plafker and Berg, 1994) shows somewhat greater offsets to the south (west of the orocline's hinge: The Kobuk-Malemute fault, which may form the northernmost of the prominent dextral shear zones, reflects ~90 km of offset; the Kaltag fault ~130 km, and the Fairwell fault ~134 km. East of the orocline's hinge, the northern Tintina fault reflects ~450 km of offset, the Denali fault ~400 km, and the Fairweather fault ~600 km; Plafker and Berg [1994]; Miller et al. [2002]), perhaps reflecting that transcurrent transport of crust increases with proximity to the plate margin.

The lack of any significant bend in the Kobuk-Malemute fault suggests that, if at all, it played a less significant role in oroclinal bending. This is not surprising since oroclinal folding, transcurrent transport, and indentation would all expectedly be greatest in southern Alaska. Nonetheless, the presence of

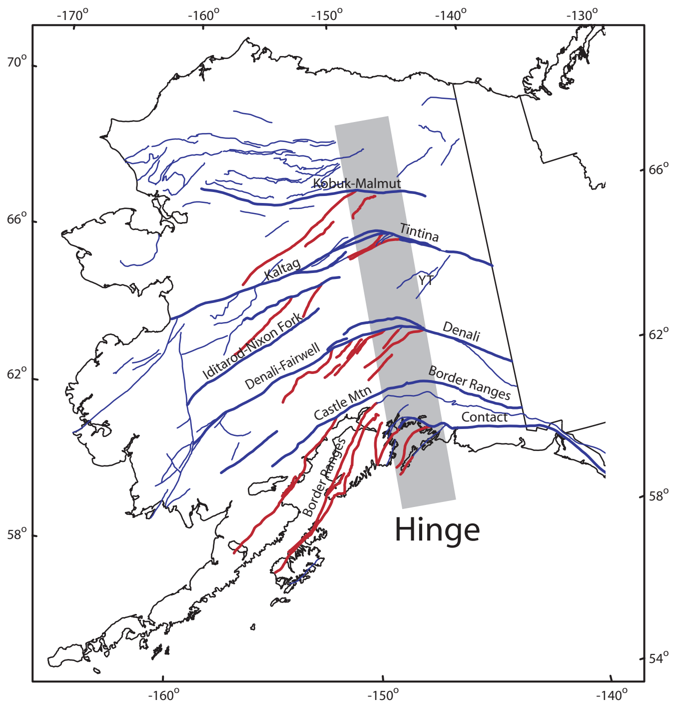


Figure 6. Primary (blue) and secondary (red) fault patterns in Alaska. Fault traces are the same as in Figure 1, but colored to signify the "family" of faults they belong to. The primary fault pattern (blue lines) reflects major through-going dextral shear zones (e.g., Grantz, 1966). The secondary fault pattern (red lines) proposed here is interpreted as a system of thrust faults that accommodate stress within the bend of the orocline due to original bending and the transport of crust through the bend due to dextral shear along the primary system of faults. A series of northeast-trending faults in the Yukon-Tanana terrane (YT) between the Denali and Tintina faults is not included in the secondary fault pattern because these faults are interpreted as part of a system of active left-lateral strike-slip faults that divide the crust into several long blocks (Page et al., 1995). The bocks are believed to be rotating in a clockwise fashion in response to north-south compression and to being bound by dextral shear zones.

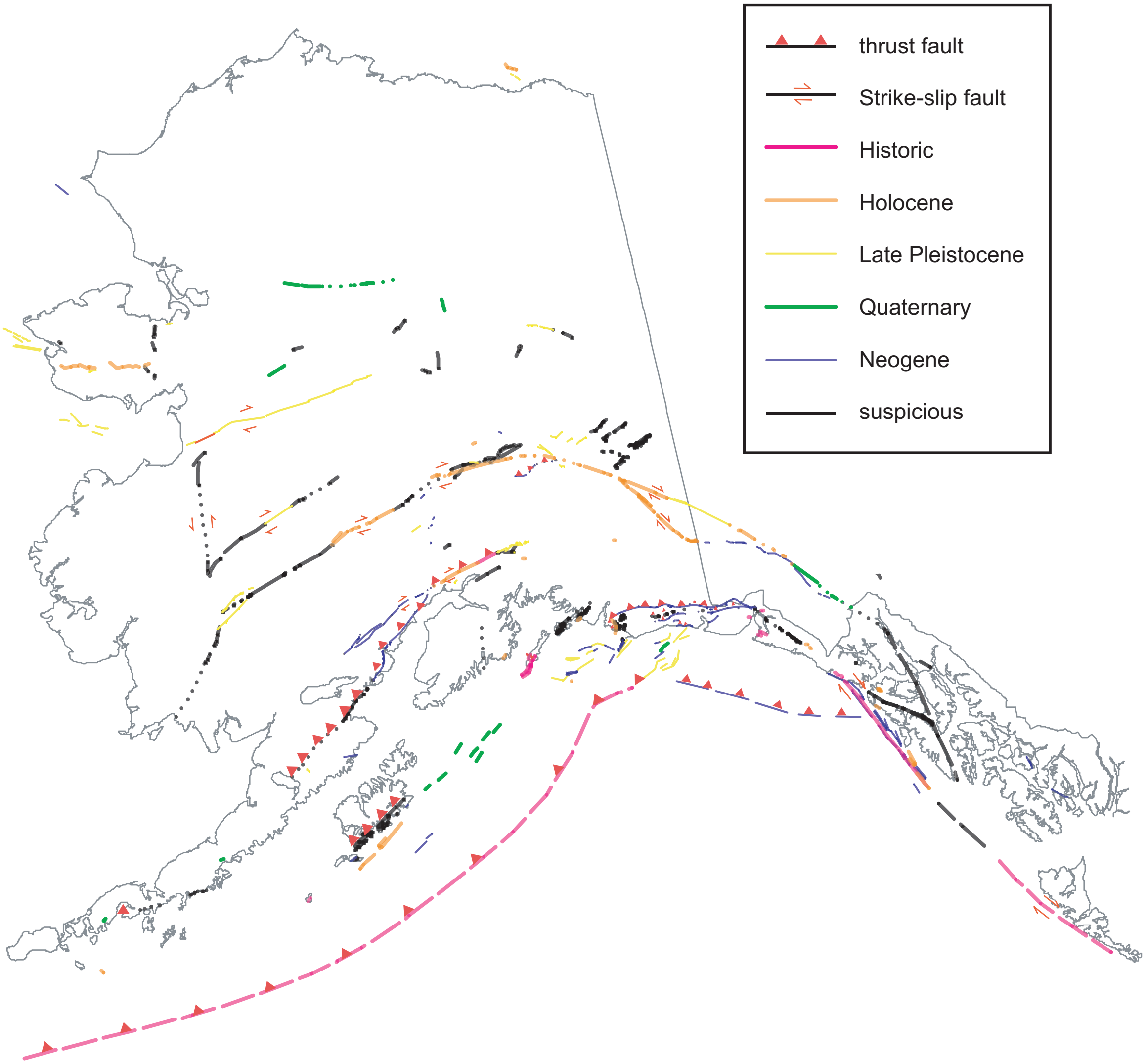


Figure 7. Neotectonic fault map of Alaska showing Paleogene faults for which there is documented sense of motion. Faults are color-coded by age of most recent activity (data are after Plafker et al., 1994a).

northeast-trending faults that splay off of the Kobuk-Malemute fault near the axis of the orocline may reflect deformation due to bending and to compression induced by later collision of terranes at Alaska's southern margin (see discussion herein on the nature of northeast-trending faults). Even further north, the timing of Tertiary uplift and thrusting in the Brooks Range, >1200 km inboard of Alaska's southern convergent margin, have been interpreted as resulting from indentation by terranes in the hinge of the orocline (O'Sullivan and Wallace, 2002).

In addition to the change in offsets from north to south, there is a contrast from east to west. Late Cretaceous and early Tertiary dextral offsets east of the hinge are significantly larger than those to the west. Some of this discrepancy is most likely taken up by compression west of the hinge but may also be accounted for by strike-slip motion on faults subsidiary to the dextral shear zones.

NATURE OF NORTHEAST-TRENDING FAULTS

Besides the primary family of arcuate right-lateral strike-slip faults, it appears that many of the remaining faults form a secondary fault pattern consisting of northeast-trending structures (red lines, Fig. 6). An important characteristic of these faults is that they splay off at or near the dextral shear zones and occur consistently west of the orocline's hinge. This relationship strongly suggests that the faults are tied to the dynamics of crustal deformation within the bend. Some of the faults (e.g., the Broxson Gulch thrust, Figs. 1 and 2), show evidence of Tertiary movement (Ridgway et al., 2002). Stout and Chase (1980), for example, suggested that the Broxson Gulch fault might have been responsible for mitigating compressional stress between what they considered distinct plates north and south of the thrust. It is here suggested that this deformation, associated with oroclinal bending and crustal transport through the bend, is accommodated by a number of similar structures, some of which have previously been considered inactive since the Mesozoic.

Indeed, the central Alaska Range, displaying some of the most rugged relief worldwide and containing Mount McKinley, the highest peak in North America, lies immediately west of the hinge of the orocline and is believed to result from thrusting on northeast-striking structures (Fitzgerald et al., 1995; Stout and Chase, 1980) similar in trend to those forming the secondary system of faults described above.

The Talkeetna Mountains (Fig. 2), which lie just southeast of the Alaska Range, are likewise ideally located within the hinge of the bend where one would expect to find evidence for orocline-related deformation. Unfortunately, the sense and timing of motion along most of the northeast-trending structures is too poorly documented to determine whether they have undergone Cenozoic thrusting as is predicted here. In south-central Alaska, faults like the Talkeetna and Tsisi fall within the family of northeast-trending faults along the orocline's west limb. Although the Talkeetna and Tsisi faults are generally considered thrusts having formed during accretion of the Wrangellia and Peninsular terranes to North America during the Mesozoic (i.e., prior to at least the Late Cretaceous; Csejtey et al., 1978), their part in a consistent regional pattern of faulting associated with the bend implies that they may be tied to the same process of crustal dynamics.

Even if the Talkeetna fault itself was not active during or since the presumed oroclinal bending, several other northeast-trending structures exist that may have played a part in accommodating shortening. For example, recent mapping has revealed a shallow Tertiary thrust immediately south and parallel to the Talkeetna fault (U.S. Geological Survey, unpublished data) that places Triassic volcanics over Cretaceous meta-flysch deposits. Although this fault segment may have experienced only a small amount of movement, it is likely that many similar faults occur within the meta-flysch or basalts, but they are difficult to discern within a single, relatively homogenous lithology (J. Schmidt, 2003, personal commun.). Numerous northeast-trending reverse faults, located northwest of the Talkeetna fault between Broad Pass and the Susitna River (U.S. Geological Survey, unpublished data), also show evidence for Tertiary movement. Their relatively steep dips may shallow at depth, resulting from steepening by imbrication, or resulting from oblique, as opposed to pure dip-slip, motion. It is possible, therefore, that these faults participated in accommodating compressional deformation due to oroclinal bending and to the transport of crust though the bend, despite their present steep surface dips.

South of the Talkeetna fault, in the vicinity of the Tsisi fault, evidence for slip is lacking due largely to poor outcrop exposure. While there is no direct evidence for thrusting on the Tsisi fault, it is clear that the structure has been active in the Tertiary (U.S. Geological Survey, unpublished data). Indeed, recent mapping has revealed folding of Tertiary volcanics near the Tsisi fault around northeast-trending fold axes and vertical offset of the basal contact of volcanic strata (an erosional unconformity cutting Jurassic intrusives) that are consistent with possible Cenozoic thrusting on the Tsisi fault (U.S. Geological Survey, unpublished data).

Despite recent mapping results, the general lack of both mapped structures and evidence of offsets is perhaps attributable to a lack of detailed mapping, poor fault exposure, and poor preservation. Due to the lack of infrastructure (and thus accessibility), the large amount of ice, vegetation, and soil cover, the extent of detailed geologic mapping (at scales of 1:100,000 or larger) is sparse. Even along the San Andreas fault, which is perhaps the single most intensely studied fault system in the world, there remains a great discrepancy between documented slip rates and what would be expected from relative plate motions of the Pacific and North American plates (Atwater, 1970). At least some of this "missing" slip is generally ascribed to other faults within a fault zone extending well beyond the principal trace of the San Andreas fault (Irwin, 1990).

Indeed, the dilemma posed by plate tectonic and paleomagnetic evidence favoring significant displacements of up to thousands of kilometers along major transcurrent fault systems and the lack of geologic evidence for faults recording 1000-km-scale translations has been recognized in a number of transform plate boundary settings (Umhoefer, 2000). This incongruity between regional tectonic and local geologic data in environments like southern Alaska may be due to the distribution of slip along several anastomosing faults distributed across a broad fault zone—where each fault accommodates a significantly small amount of offset compared to the total—as opposed to a single large fault trace. In addition, due to the nature of a broad complex fault zone, many companion faults are likely to be destroyed or reactivated during the life of a transcurrent system, leading to the complete or partial overprinting of their slip histories. For these reasons, detailed mapping may under-represent displacements and structures necessary to account for movement predicted from regional mapping and tectonic studies.

REGIONAL SEISMICITY

Until recently, the region within the bend around the Talkeetna Mountains was poorly instrumented with seismometers. As a result, both earthquake foci and focal mechanisms are poorly determined. Nonetheless, existing relocated earthquake data indicate that faults within the Talkeetna Mountains are presently active. Relocated epicenters (data from Ratchkovsky et al., 1998; N. Ratchkovsky, 2002, personal commun.) of recent events in and around the Talkeetna Mountains show a preponderance of activity just north of the Talkeetna fault and the lack of events immediately south of the fault (Fig. 8). While the foci are diffuse and do not appear to indicate a single thrust plane, their distribution might, for example, result from elevated stresses in an overriding northwest crustal block imposed by southeast-vergent thrusting along the Talkeetna fault zone. In fact, preliminary potential field modeling of dense magnetic bodies south of the Talkeetna fault suggests that the fault dips to the northwest (Glen et al., 2002), consistent with a scenario of a northwest-dipping thrust.

CLUES FROM THE RECENT DENALI M7.9 EARTHQUAKE

The November 3, 2002, M7.9 Denali fault earthquake marked the largest recorded seismic event in central Alaska and along the Denali fault system, and represents one of the largest worldwide strike-slip events over the past two hundred years. Field observation of surface rupture, first-motion studies, and aftershock locations reveals a complicated rupture evolution (Eberhart-Phillips et al., 2003). The dynamics of the event are described as a multi-phase process involving a focal mechanism that changed during rupture. Rupture occurred along several different fault segments, which, combined, form an arc whose trend curves through 40°. The initial phase of slip was defined by a thrust event (M7.2) on a previously unknown, northeast-trending fault (strike = 221°, dip = 35°: Ji et al., 2002; or dip = 48°: Ratchkovski et al., 2002) now named the Susitna Glacier fault (Craw et al., 2002). This was followed 15 seconds later by the main event that ruptured unilaterally eastward over 300 km and was dominated by right-lateral strike-slip motion on the east-southeast Denali fault and then stepped to the Totschunda fault. Some vertical motion occurred on the Denali fault (north side

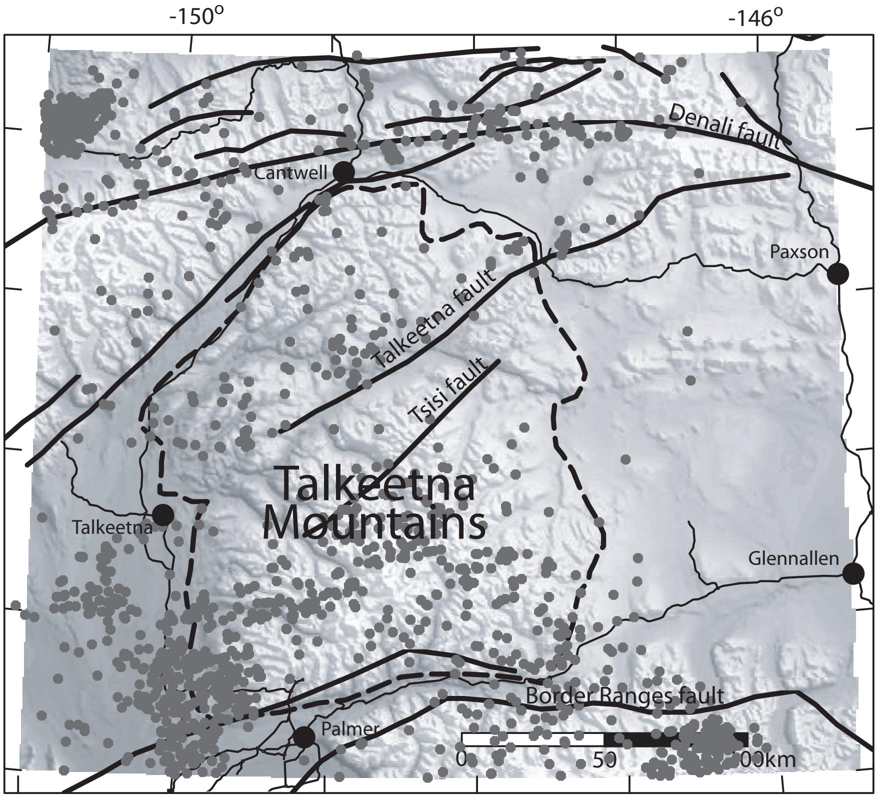


Figure 8. Epicenters (gray dots) of relocated earthquakes (from Ratchkovsky et al., 1998; N. Ratchkovsky, 2002, personal commun.) extending to a depth of 50 km plotted on topography. A preponderance of events just north of the Talkeetna fault and the lack of events immediately south of the fault may result from active southeast vergent thrusting producing increased stresses in the overriding crustal block. Faults are shown in bold black and roads appear as thin, black lines. Bold dashed line outlines the Talkeetna Mountains.

up); however, focal mechanisms suggest that the fault is nearly vertical (Ratchkovski et al., 2002). Thus, both the initial thrust and subsequent strike-slip motion of the Denali event are consistent with the orocline model (Glen, 2001) presented here.

Further clues that the family of northeast-trending faults proximal to the hinge is presently active come from the aftershock pattern of the Denali event and that of a M6.7 precursory event that occurred 11 days earlier and roughly 25 km to the west along the Denali fault (Fig. 9). Aftershocks are clustered along the Denali fault between major mapped northeast-trending faults, suggesting that stress domains along the Denali fault are controlled by the northeast-trending faults. For example, the southeast aftershocks of the Denali main event are bound on the north by the northeast-trending Broxson Gulch thrust, whereas the northwest patch is bound on both the west and east by mapped, but unnamed, northeast-trending faults.

KINEMATIC MODEL OF REGIONAL FAULT PATTERN

As a simple analog for how the secondary fault pattern accommodates strain due to bending and the continued westward translation of crust along dextral shear zones, consider an airport luggage carousel (Fig. 10). As the conveyor turns the corner, shortening is accommodated by the relative rotation and overlap of adjacent leaves. In a like manner, arcuate dextral shear zones such as the Denali fault accommodate lateral transport of crust (similar to the top and bottom of the "conveyor belt"), while northeast-trending thrusts such as the Talkeetna accommodate deformation within the bend (similar to the overlapping edges of the conveyor's leaves).

Thus, east of the hinge, one would expect to find primarily strike-slip faults associated with the transport of crust, whereas west of the hinge, one would expect to find thrust faults associated with crustal deformation. Indeed, Bol and Gibbons (1992) demonstrate that in southern Alaska in the Prince William Sound region east of the hinge, faults (even those that are shallow-dipping) largely reflect dextral strike-slip motions, whereas to the west, faulting is reverse.

This mechanism might apply, in a general way, to any restraining bend. For instance, faults like the Banning and Sierra Madre–Cucamonga, which occur within the bend of the San Andreas fault in the Transverse Ranges (Weldon and Humphreys, 1986), resemble the secondary northeast-trending faults in south-central Alaska. Though the conveyor model may be relevant to a potentially broad range of tectonic environments, it likely oversimplifies certain aspects of crustal dynamics. For example, because deformation has mostly affected southern Alaska, not all of the faults are expected to have experienced the same type or degree of slip implied by the model. Additionally, movement along exceptionally long fault traces (e.g., the Border Ranges fault) may be due to different sources of stress at different places along the fault, warranting their inclusion into both fault families.

Unlike the simple conveyor model in which overlapping leaves incline in the same direction, crust within the bend is not constrained to deforming along faults with the same dip. Northeast-trending faults, having either northwest or southeast dips, can both accommodate compression. Furthermore, strike-slip and thrust faulting are not necessarily confined to primary and secondary faults, respectively; some strike-slip motion may occur on the northeast-trending faults, and some thrusting may occur on the primary dextral faults. Indeed, it appears that in places where the dextral faults splay and shallow in dip, they accommodate thrusting (Ridgway et al., 2002).

Another difference between the orocline and conveyor model dynamics relates to the fault motion as crust moves through the bend. In the case of the conveyor, the leaves rotate back to their original position as the conveyor belt moves out of the bend (i.e., thrusting, experienced as crust moves into the bend, changes to normal faulting as crust moves out of the bend). In the case of the orocline, however, crust may have been prohibited from extending due to compression imposed on the west limb by the subducting plate. In fact, because Pacific–North American plate convergence changed to orthogonal transpression in the middle Eocene to early Miocene (42–23 Ma), due to counterclockwise

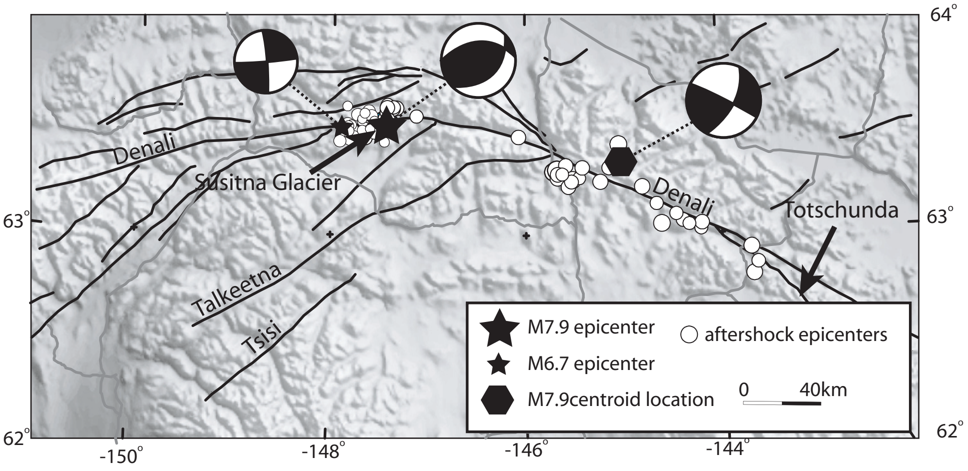


Figure 9. Epicenters for the principal earthquakes and aftershocks associated with the M7.9 Denali fault earthquake for November 3, 2002 (Alaska Earthquake Information Center, 2003). Labels refer to selected faults. Although the trace of the Susitna Glacier fault is not shown, its location is indicated by the arrow and corresponds roughly with the M7.9 epicenter. Focal mechanisms show the first motion solution for the M_W 6.7 foreshock, the M_W 7.9 main shock, and for the centroid of the main event. Aftershocks are those that occurred November 3, 2002.

rotation of western Alaska, transport of crust through the bend and the development of thrusts may have slowed or even ceased.

A distinction can also be made between deformation due to oroclinal bending and that due to the transport of crust along dextral shear zones. Although the northeast-trending faults can accommodate deformation in either case, the timing of fault activity would differ. In the case of oroclinal bending, thrusts throughout southwestern Alaska would be activated simultaneously. In contrast, thrusts generated by the transport of crust through the bend initiate near the hinge and subsequently become inactive (or even change to normal faults) as crust moves away from the hinge. In this case, the youngest and most active thrusts would occur immediately west of the hinge and older thrusts further westward. Indeed, the extreme and relatively young uplift history of the Alaska Range (e.g., rapid uplift of the Alaska Range has occurred over the past 5 m.y.; Plafker et al., 1992; Fitzgerald et al., 1993, 1995), occurring just west of the hinge, is consistent with uplift due to the transport of crust through the bend of the orocline along dextral shear zones. Additional causes for uplift may include Pacific plate subduction and collision of the Yakutat plate.

A PRESENT-DAY ANALOG

A deformation process similar to that which seems to be occurring in central Alaska may be occurring at Alaska's southern margin where the crustal block most recently accreted to the continent, the Yakutat terrane (Fig. 11), is presently working its way into the bend of the orocline (Plafker et al., 1994b). The Yakutat terrane has a distinct structural zone on its western end where rocks are deforming in a <120-km-wide fold and thrust belt. This belt occurs where late Cenozoic underthrusting of the Prince William terrane continues into the present (Plafker et al., 1994b). Similar to the structures observed in central Alaska, the Yakutat deformational front is marked by a series of northeast-trending thrust faults that occur at the bend of the principal bounding strike-slip fault that acts as a backstop to the terrane (Fig. 11). Note, however, that because the Yakutat terrane still lies east of the bend of the orocline, the equivalent hinge for the terrane, corresponding to the bend in the bounding fault (Fig. 11), lies east of the orocline's hinge (Fig. 6). In light of this, the pattern of thrusts within the deformation front of the Yakutat terrane resembles that seen in central Alaska—the faults occur at, and west of, the hinge. Since the Yakutat is the most recent and outboard terrane to accrete to southern Alaska, and is still migrating into the bend, it lacks the complications imposed by multiple deformations of the central Alaskan terranes. As such, it represents a simple analog for deformation due to convergence within the hinge of the orocline.

CONCLUSIONS

Southern Alaska terranes are transported through the Alaska orocline by dextral movement along a primary set of major arcuate faults like the Denali and Tintina. This transport, and the initial bending of the crust to form the orocline, resulted in significant crustal shortening within the bend that, as suggested here, is accommodated by thrusting along a secondary family of northeast-trending faults. The distribution of these secondary faults shows a consistent pattern within the bend—they appear to splay off at or near the major dextral shear zones and generally occur west of the hinge of the Alaska orocline. The occurrence of these faults where deformation would be greatest as crust moves through the bend suggests that the faults are directly related to crustal dynamics within the bend.

Rupture during the recent M7.9, November 3, 2002, Denali earthquake, appears to support this model of crustal deformation. Slip during the Denali earthquake sequence, which occurred along several different fault segments, initiated with movement along a northeast-trending thrust fault located within the bend. This was followed by unilaterally eastward slip over a 300-km-long segment that was dominated by right-lateral strike-slip motion on the east-southeast Denali and then Totschunda faults. Thus, both families of faults were represented in this single large event.

A present-day analog for crustal deformation of interior Alaska occurs in southern Alaska where the Yakutat terrane is actively accreting and migrating into the bend. Fault patterns at the northwest margin of the Yakutat terrane closely resemble fault patterns in the hinge of the orocline in central Alaska. Deformation of the Yakutat terrane therefore provides further clues to the early stages (e.g., post–late Cretaceous) of crustal deformation in central Alaska.

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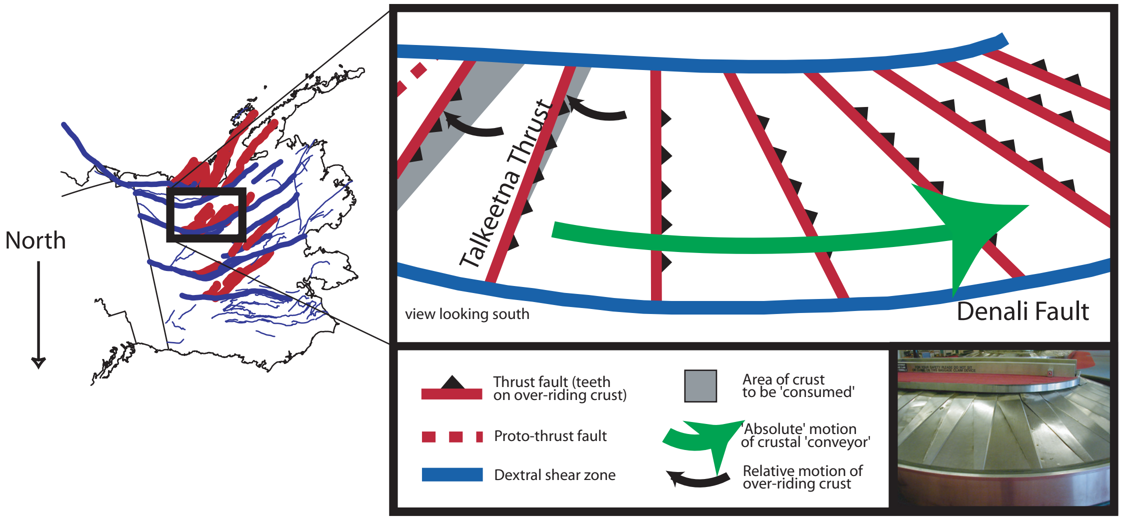

Figure 10. Luggage carousel model for the tectonics and geometry of faulting within the Alaska orocline. The fault pattern in southern Alaska (view is looking south) is likened to the mechanics of a luggage carousel that moves from left (east) to right (west).

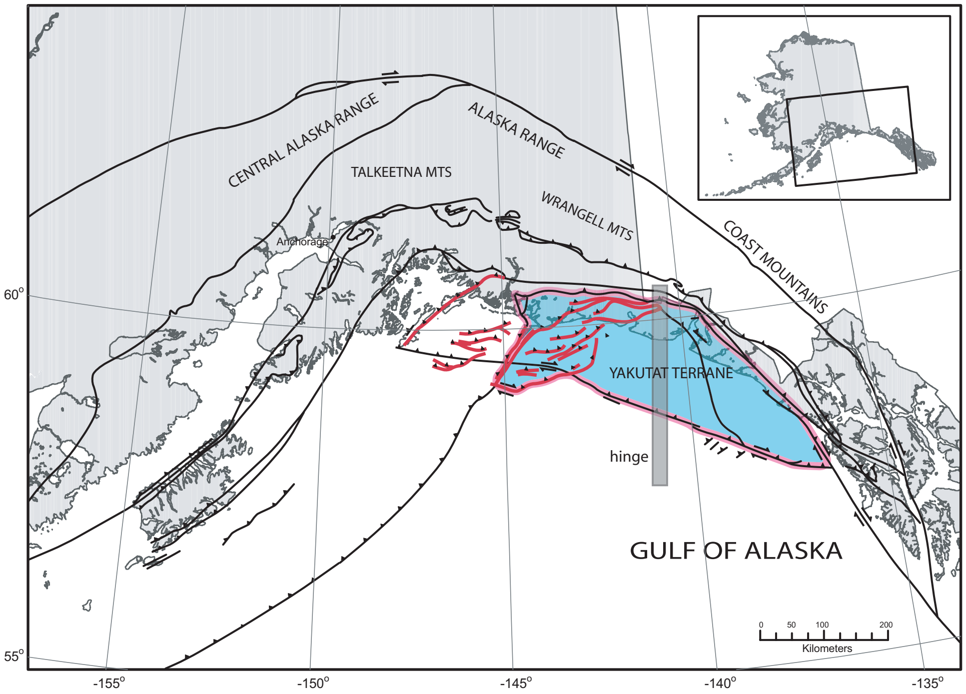

Figure 11. Map of southern Alaska tectonostratigraphic terranes and faulting associated with the Yakutat terrane (modified from Plafker et al., 1994b, their Figure 6).

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